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ABSTRACT:

Self-lubricating bearings have been demonstrated to provide a positive impact in countering deleterious tribological circumstances occurring in normal compressor operation. But they have typically been unable to meet tight tolerances associated with more conventional bearing types such as leaded bronze or bi-metal bushings. Materials with homogeneous composition such as bronze bushings are capable of being machined to a significant depth without changing the tribological performance of the sliding interface. By comparison, self-lubrication bushings with a layered metal / polymer construction have historically been shown to undergo a reduction in performance as a result of sizing operations after assembly such as machining or extensive burnishing. An investigation was conducted to evaluate the effect of burnishing on tribological performance on a variety of self-lubricating bearings. This was done to investigate whether compressor performance and life may be sustained when self-lubricating bearings are utilized to mitigate compromised lubrication in combination with sizing methods to achieve optimum compressor efficiency. Significant burnishing levels were achieved with no measurable reduction in polymer bearing wear life.

1.0 BACKGROUND:

Compressor applications utilize a range of bearing types to facilitate shaft rotation necessary to perform the pumping action which creates the compressor function. These include bronze bushings (some containing lead) and polymer-lined plain bearings. Metal-polymer bushings have been demonstrated to provide favorable performance in a broad range of compressor applications including high efficiency and extended compressor life. The type of polymer bushing used most frequently in compressor application is shown in Figure 1 exhibiting the cross-section of the functionally graded composite structure. This multi-layer construction consists of: i) a steel backing that acts to support the wear components ii) a porous bronze layer of approximately 30% porosity, filled with a polymer impregnant and iii) a polymer layer on top of the bronze of the same composition as the impregnant within the bronze, commonly called the overlay. The polymer bearing used most widely in compressor application has utilized a filled polymer composition of PTFE with 20 v/o lead filler, and overlay thickness of approximately 25 μm. This composition has lost favor in many compressor applications as the element lead has been targeted for elimination. This is also the case for many of the bi-metal used in compressor applications, indicating that a comprehensive material solution providing favorable tribological performance and optimum efficiency would be viewed favorably by the industry.

Accurate dimensional tolerance and small clearance range between shaft and bushing improve compressor efficiency, a significant point for modern compressors. Previous work in this area (Small, 2006) showed that compressor efficiency was higher with metal-polymer bushings than with bi-metal when clearance was in a desired range. The efficiency data, shown in Fig 2, which considered the horizontal "zero" line to be the efficiency of a scroll compressor with leaded bi-metal bushings indicated that polymer bushings had over 3% higher efficiency with clearance that was controlled as tightly as with bi-metal. The comparative clearance ranges for bi-metal bearing and metal-polymer bushings are shown with the preferred clearance range being approximately 25 μm between minimum and maximum for both the bi-metal and polymer bushings, although offset from one another. That clearance range, however, was shown to be smaller than can typically be achieved with polymer bushings that are used in the "as-installed" condition. This inability to control clearance sufficiently has resulted from variation in both the metal-polymer wall thickness and tolerance of the housing into which it is installed. Secondary sizing operations can mitigate the combined tolerance of both components.

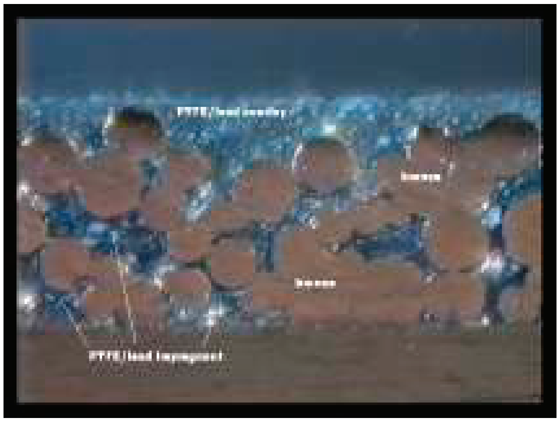


Figure 1: Typical cross-section of PTFE/lead metal-polymer bushings

Table 1: Effect of burnishing on life of Metal-polymer bushings

Burnishing Interference (μm)	Life Reduction
25	20%
38	40%
50	70%

Metal / polymer bushings are often preferred to bi-metal in sliding applications because friction is lower for the PTFE-based composite, and the ability to self-lubricate during periods of marginal or insufficient lubrication improves compressor reliability. Most compressors types utilizing metal-polymer bushings have typically used them in the "as-installed" state, limiting the dimensional tolerance and clearance range to the combined tolerance of the components in the sliding system. These are the housing, bushing and shaft, each with its own dimensional variation. The reason for this limiting of post-installation size adjustment is that such procedures have been shown to reduce bearing life (GGB DU Design Guide, 2008). Table 1 shows the effect of burnishing on the life of a PTFE / lead bushing, with a 70% life reduction predicted from a burnishing tool of 50 μm interference; that is, difference between burnishing tool diameter and installed bearing internal diameter. Bi-metal bushings, by comparison, can be modified to establish tighter dimensional tolerance using machining to establish the bearing bore after installation with no apparent loss of tribological performance or bearing life. The work described below was conducted to investigate the possibility that a polymer bearing used for its favorable tribological properties may also be modified to achieve the same developed dimensional tolerance of a rolling element bearing or bi-metal bushing.

Further demonstration of clearance ranges for polymer bushings is indicated below for two production compressors, one with a nominal 17 mm shaft diameter; the other 41 mm. Clearance range was determined in the design phase utilizing the maximum dimensional tolerance of the three components: shaft, housing and bushing. The as-installed clearance of the two compressors was:

17 mm ID:	Min: 10 μm	Max: 80 μm	Range: 70 μm
49 mm ID:	Min: 34 μm	Max: 109 μm	Range: 75 μm

These clearance ranges were approximately 50 μm larger than the 25 μm target range for maximum efficiency. Methods to re-size polymer bushings following installation have been utilized to develop clearance ranges that are narrower than is possible in the as-installed state. A study was conducted to investigate the level of size adjustment via burnishing that could be utilized while maintaining acceptable bushing life.

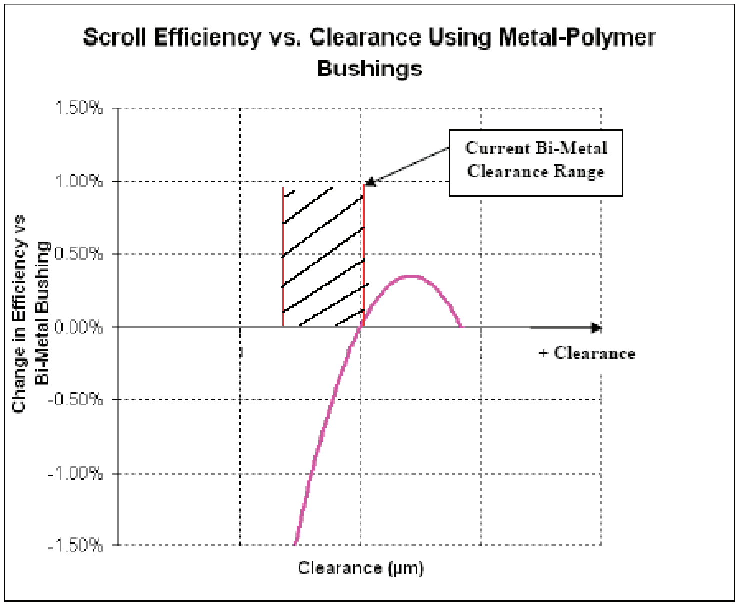


Figure 2: Efficiency as a function of clearance between shaft and bushing[1]

The baseline target bearing life was considered for this study to be that life measured for a standard PTFE / lead bushing of the type referenced above. This bearing type has long been used in the compressor industry in a broad range of compressor types and was therefore considered to provide acceptable life and friction performance. As stated above, it has lost favor because of its lead content, not its tribological performance. It was therefore considered to provide a good baseline performance level for comparison within this study. A second bushing type of the same basic construction, but with a liner composition of PTFE / CaF_2 was utilized in the burnishing trials.

2.0 Burnishing Trials

Bushings of 20 mm nominal inner diameter were installed into a fixed ring, and supported to allow a burnishing tool to be progressed through the bushing bore. The study used bushing of 20 mm nominal I.D.; 23 mm nominal O.D. Burnishing procedures and tool design are reported elsewhere (GGB DU Design Guide, 2008). The burnishing tools were pushed through the installed bushing using an Instron unit with load cell connected to a digital recording system. The bushing internal diameters and diameter of the burnishing tools were measured before and after burnishing. The interference for each test was calculated as the difference between the measured ID of the bushing and the maximum diameter of the burnishing tool. Force required to push the tool through the bushing was measured and recorded, as was the internal diameter of the bushing after burnishing.

Figure 3 shows force data required to perform the burnishing operations as a function of burnishing tool interference. The data in Figure 4 show the relationship between the burnishing tool interference and final bushing bore dimension, plotted as diameter increase.

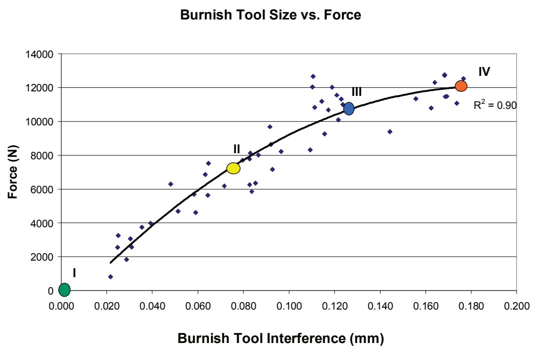


Figure 3: Burnishing force as a function of interference

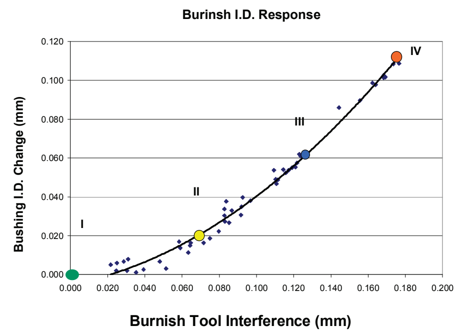


Figure 4: Diameter change as a function of interference

3.0 Tribological Testing

Compressor operation imparts a combination of tribological conditions upon a plain bearing resulting from relative sliding between shaft and bearing combined with a compressive load that continually changes location around the bore circumference. Both polymer and metal plain bearings must therefore survive a combination of conditions including sliding wear and cyclic compressive loading. Tribological testing was conducted to identify the effect of burnishing was conducted in a test unit that that simulated those conditions.

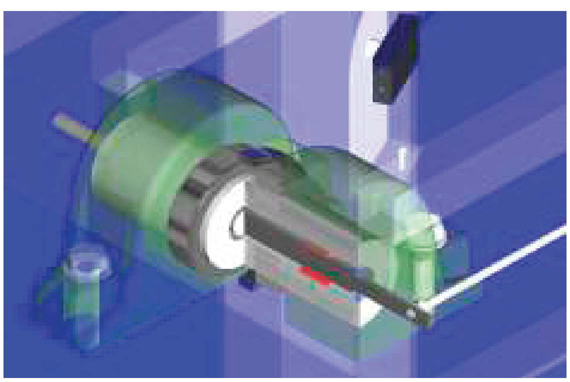


Figure 5: Cutaway illustration of wear tester with rotating housing, stationary shaft

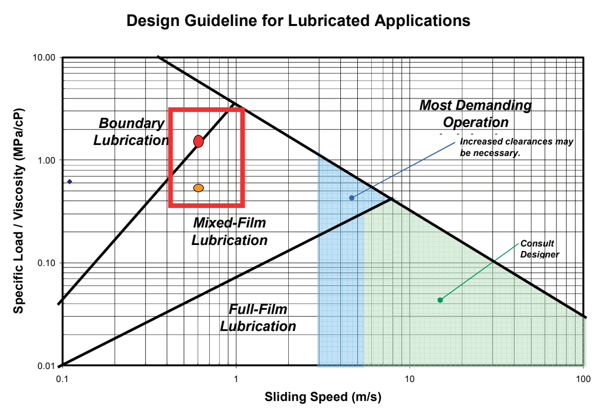


Figure 6: Lubrication state map indication condition at startup and following frictional heating

Tribological performance of the burnished parts was evaluated utilizing a test rig capable to impart both sliding conditions and cyclic loading simultaneously. This was done with the bushings installed in a cylindrical housing, with a shaft installed as shown in Figure 5. That image is a cutaway illustration of the test unit that contained a housing with two bushings capable to support the test shaft. The shaft was fixed to prevent rotation. Load arms with fixed weights applied the test load while the housing was driven in rotation. The housing was filled with DTE 25® oil, with seals inserted in the ends of the housing to contain the oil. This combination of conditions caused relative sliding between bearing and shaft and imparted continual cyclic compressive loading as the bushings rotated constantly relative to the load location.

Nominal specific load was 3.4 MPa (500 psi), but edge loading from shaft deflection increase actual specific load to 18 MPa (2,600 psi). The housing was rotated at 750 rpm, providing a surface sliding speed of 0.78 m/s (153 ft/min). Shaft surface finish was 0.12μm R_a (5 μin). Tests were conducted at ambient temperature (25°C), but frictional heating increased the oil temperature to approximately 95°C under normal operating conditions. Test duration was 200 hours.

The oil film conditions were calculated using the graph in Fig. 6. This lubrication state map includes the primary oil film conditions: boundary, mixed film and hydrodynamic film lubrication. The two points shown within the rectangle indicate the range of oil film conditions present during this work. The lubrication state at startup was calculated to be in the mixed film state. Frictional heating increased the oil temperature, reducing viscosity and causing a transition to boundary lubrication. This condition provided a set of conditions favorable to evaluate the effect of the burnishing operation on bushing life at the cyclic loading combined with boundary lubrication imparted conditions of both wear and fatigue. Figure 8 shows wear data for the series of burnished bearings. This graph shows wear depth for the full range of PTFE / CaF_2 to have been in the range of 0 to 5 μm. By comparison the baseline PTFE / lead bushing type showed wear of approximately 40 μm.

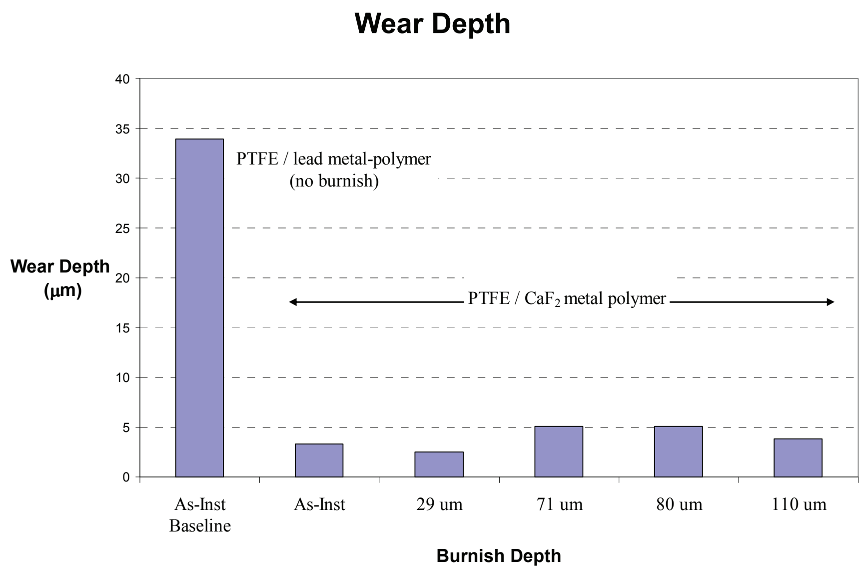
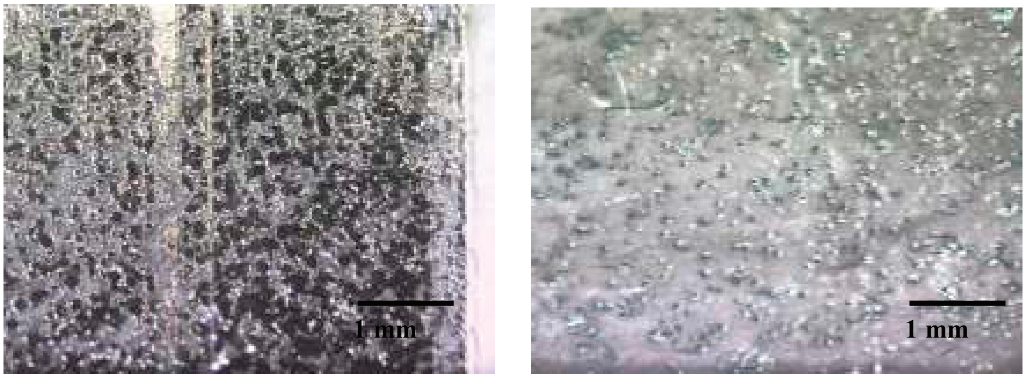


Figure 7: Wear depth as a function of burnishing depth in comparison to baseline material

Examples of the load zones of tested bearings are shown in Figure 8. A notable difference is evident between the PTFE/lead and PTFE/CaF_2 bearings regarding the fraction of bronze particles visible in the wear surface. A greater fraction of exposed bronze relative to the PTFE in the surface for the PTFE/lead was indicative of deeper wear below the initial bearing surface. The useful life of the bearing was considered to be consumed at a wear depth of approximately 65 μm, at which point the surface typically has in the area of 70% bronze exposure. The reduced PTFE content of the wear surface at this point is associated with a friction increase that is usually considered to be deleterious to system performance.

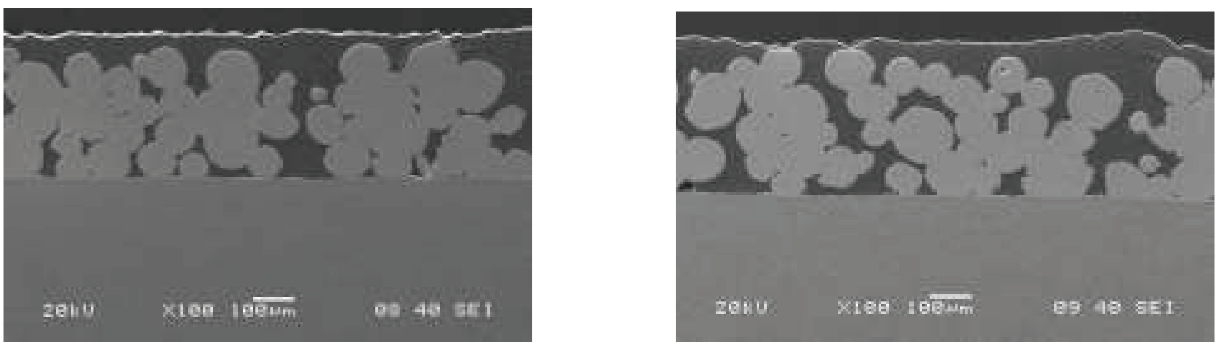
Fatigue of the polymer surface was considered to be a possibility with the loading scheme used in this work; that was, cyclic compressive loading of the bearing surface superimposed with relative sliding. Cyclic loading can result in subsurface cracking that could lead to spalling or delamination of the polymer overlay. This loss of the low-friction polymer layer can then result in increased friction and wear as the underlay bronze structure is left to slide directly against the opposing steel shaft. This was considered to be an even greater risk as the burnishing level was increased and the possibility of subsurface deformation was considered. No surface delamination within the load zone of the tested metal-polymer bearings was observed, as exhibited in the wear surface examples in Figure 10. Further investigation of the tested bearings was conducted using electron microscopy to observe tested bearing cross sections. Two examples of the images are shown in Figure 9, produced from tested bearings with 30 and 110 μm burnishing. No subsurface cracking indicative of fatigue damage was evident in the cross-sections.



PTFE / lead bushing
33 µm wear loss
(A)

PTFE / CaF_2 bushing
5 µm wear loss
(B)

Figure 8: Wear surfaces after testing



30 µm burnish
(A)

110 µm burnish
(B)

Figure 9: Cross-sectional images of tested PTFE / CaF_2 bushings

4.0 SUMMARY

The goal of this work was to evaluate whether polymer bushings could be burnished to significant levels without measurable loss of bearing life. Bushings were burnished to levels in excess of 100 microns, to evaluate the effect on life in an operating environment in which the bearing experienced both sliding wear and compressive fatigue. Wear data showed that bearing life of a lead free PTFE / CaF_2 bushings at all burnishing levels was the same or greater than the baseline PTFE bushing material in the unburnished state. This demonstrated significant potential to provide a material solution with tribological performance for which polymer bearings are favored while provide the potential for tight dimensional tolerance through secondary operations.

5.0 REFERENCES

1. Small, Christopher D. “Compressor Applications: Metal-Polymer Vs. Traditional Bearings” *Mechanical Engineering Web Exclusive*. 11 Dec. 2006. http://www.memagazine.org/contents/current/webonly/wex121106.html

2. GGB Bearing Technology, “DU Design Guide.” www.ggbearings.com/pdf/literature/manuals/US-Format/DU-us.pdf.